

EXPERIMENTAL INVESTIGATION AND COMPARISON OF FLANK WEAR AND SURFACE ROUGHNESS IN TURNING OF AISI 4340 STEEL USING CERAMIC COATED AND UNCOATED CARBIDE INSERTS

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ABSTRACT

Carbide inserts are most widely used for machining alloy steels which have wide applications in the industries. The present work is to investigate the influence of cutting parameters on surface roughness and flank wear in comparison with coated and uncoated carbide inserts. In this context, a single layer of titanium nitride (TiN) coating of 2µm thickness has been applied by the process of physical vapor deposition (PVD) on the carbide tool insert. The experimentation is carried out on AISI 4340 medium carbon alloy steel at multi-level cutting parameters. In this regard, a partial level mixed factorial was considered and an L18 orthogonal array is generated by design of experiments (DOE) in MINITAB15. Analysis of Variance (ANOVA) at a confidence level of 95% is used to analyze the effect of turning parameters on the responses. It is found that the type of insert is the most influencing parameter for both surface roughness and flank wear. However, a feed is the next influencing parameter on surface roughness and speed, feed on the flank wear. Scanning Electron Microscope (SEM) analysis was done for the coated and uncoated cutting inserts and the machined surface of the workpiece at the optimized cutting parameters obtained through the Main effects plots. It is known that TiN coating possesses high wear resistance, good thermal stability and low coefficient of friction, which results in the better performance of the coated inserts as compared to the uncoated inserts in all given machining conditions. The flank wear and surface roughness are affected by ploughing effect, burring and formation of built-up edges (BUE) which are found to be less in the coated inserts.

KEYWORDS: Carbide Inserts, Titanium Nitride Coating, SEM Analysis; Flank Wear & Surface Roughness

Received: Jul 23, 2018; **Accepted:** Aug 13, 2018; **Published:** Sep 10, 2018; Paper Id.: IJMPERDOCT201838

INTRODUCTION

In the field of manufacturing technology, there has been a tremendous development and thereby the use of cutting tools has also increased to a greater extent. This has encouraged the use of ceramic tools for the purpose of machining to meet the demands of a higher surface finish and faster machining. Thus the ceramic tools have proved to be better than tool steels for the machining of hard workpiece materials. For machining, the cutting tool should be twice as hard as the workpiece. The most common among the carbides is the tungsten carbide. The Carbide tools perform well at higher temperatures at the tool workpiece interface than standard high-speed steel tools. Carbide is usually superior for the cutting of tough materials such as carbon steel or stainless. Carbide is expensive as compared to other tool materials, and it is more brittle, making it vulnerable to chipping and breaking. To avoid this problem, the carbide inserts are used placed in a larger tool holder whose shank is made of another material, usually carbon tool steel. This benefits the use of carbide without the high cost and brittleness of making

the entire tool out of carbide. As the performance of the workpiece material increases in terms of its hardness, the performance of carbide tool decreases and it leads to problems of quicker flank wear, lower surface finish during machining thereby affecting the tool life. To increase the life of carbide tools, they are sometimes coated with special hard coatings. Generally, the tool's hardness is increased by the deposition of the coating. A coating allows the cutting edge of a tool to cut through the material without sticking to it.

The coating also helps to decrease the temperature at the tool-work interface and increases the life of the tool. The coating is usually deposited via thermal chemical vapor deposition (CVD) and also with the mechanical or physical vapor deposition (PVD) method. Today in the machining of ferric materials, the cemented carbides are coated with titanium nitride (TiN) for better performance of carbides at extreme machining conditions. Based on the study conducted by Shanyong Zhang et al.[1]. TiN coating on the high-speed tool steel has proved to be a success in improving the productivity and reducing the machining costs. It has also been concluded in his work that PVD process of the coating on HSS tool has been more appropriate as compared to CVD process even though PVD process has its limitations. Pratik L et al. [2] also conducted experiments using TiN coated tool inserts on AISI4140 and their results concluded that the cutting forces in case of TiN coated inserts were less as compared to the uncoated tools. At higher speeds, the surface finish obtained was much better than the uncoated tool and the flank wear rate was also lower in the TiN coated tool [2]. The results suggested by Shivdev Singh et al. [3], indicate that in case of CVD process on a cryogenically treated carbide insert, the flank wear increases with the cutting speed as compared to the uncoated cryogenically treated insert. The machining time influences surface roughness the most followed by feed rate and cutting speed. The principal factor influencing the tool life is the cutting speed [3]. S. R Das et al. [4] conducted experiments on AISI 4340 using coated carbides; they concluded that Feed rate has the greater influence on the surface roughness as compared to the other cutting parameters and with increasing feed rate the surface roughness increases. The increase in cutting speed reduced the surface roughness. Under the dry cutting conditions, the performance of TiN coated HSS tool has been better as compared to the uncoated tool due to reduced wear at the tooltip and enhanced heat dissipation Abrar A. Arshi et al.[5]. The machinability study by N Balasubramanyam et al.[6- 11] with the coated carbide tool using PVD and CVD processes showed that PVD process of titanium alloy, presented improved results than AlCrN-T coating suggesting that it can be used with acceptable levels of productivity. The number of levels of the coating is also an important factor in influencing the performance of a carbide tool. The results of the work carried out by S. R. Das et al. [7] suggest that the performance of multi-level coating of TiN on carbide tools is better than the single level coating. Bulk tool material is retained by coated cutting tools may be due to the presence of the coating; at the toolchip interface the coating suppresses high-temperature generation, this leads to reductions in dissolution wear as suggested by M Narasimha et al. [8, 12-13]. The optimization of the turning parameters was carried out by M Kaladhar et al. using the Taguchi technique to determine the process parameters and the influence on the output parameters of surface roughness and flank wear. By the usage of coated carbide tools machining of hard materials at higher speed is improved. The experimental investigation portrays that coated tools give better results as compared to uncoated tools in turning. The stresses occurring in TiN coated carbide inserts are much lesser in comparison with the uncoated inserts due to the application of the coating [2].

Thus the present work focuses on the dry turning of AISI 4340 steel with TiN coated carbide inserts and uncoated carbide insert to explore the influence of cutting parameters and the responses on the surface roughness and flank wear by employing the Taguchi method to optimize the parameters and by carrying out the analysis in ANOVA. The comparison of both the tools has been done to verify their performances under extreme machining conditions.

MATERIAL AND EXPERIMENTAL METHODS

AISI 4340 is selected as the workpiece material because of its high strength and toughness, particularly in large sections. This material is a low alloy, medium carbon steel possessing high tensile/yield strength finding its applications in automobile axles, heavy duty shafts, spindles, gears, molds, chucks, and couplings. The workpieces of diameter 25mm and length 300mm were selected for turning, of which 50mm is for chuck holding and 250mm is turning length. A central hole is made for each face of the workpiece to accommodate the grip for the tailstock. Initially, the workpiece is ensured to be free from oxide layers dimensional inaccuracies. The chemical composition of the workpiece material is shown in table 1.

Table 1: Chemical Composition of AISI 4340 Steel (%)

Fe	Ni	Cr	Mn	C	Mo	Si	S	P
95.762	1.825	0.8	0.7	0.4	0.25	0.225	0.04	0.0350

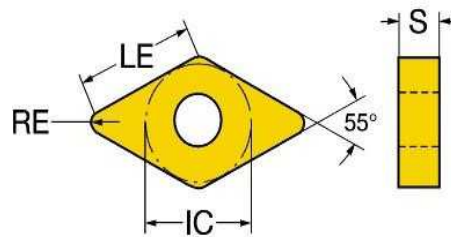


Figure 1: Geometry of Cutting Insert

Carbide inserts are most commonly and widely used a tool in metal removing operations particularly in turning. A commercially graded Carbide inserts with four cutting edges, make of SANDVIK Cormorant, DNMG 11 04 08 - PM with Grade 4325 is selected as the cutting tool. The tool geometry is shown in figure 1.

Inscribed circle diameter (IC)=9.525 mm Cutting edge effective length (LE)=11.228 mm Corner radius (RE)=0.397 mm

Insert thickness (S)=4.763 mm

Tool holder, PDJN R 25 25 M 11, from the SANDVIK Coromant make having Tool cutting edge angle - 93 deg, Tool lead angle -3 deg, Rectangular shank -metric: 25 x 25, Maximum ramping angle - 27 deg, Workpiece side body angle - 0 deg, Machine side body angle- 0 deg, Maximum overhang - 29.7 mm, Shank height - 25 mm, Functional width - 32 mm and Functional height - 25 mm is selected. Carbide inserts when inserted into the tool holder maintained a lip angle of 55 deg, clearance, back rake, and inclination angle of 6 deg and a nose radius of 0.8mm. Carbide inserts were coated with a ceramic Titanium Nitrite (TiN) PVD coatings by the process of half-ionization magnetic sputtering forming a layer of 2-micron thickness. These inserts were compared to the conventional carbide inserts in the aspects of tool wear and surface roughness of the machined workpiece. The experimentation is carried out on a CNC lathe machine with a variable spindle speed of 45-2000 rpm. Tool flank wear (VB) is found from a metallurgical microscope with a provision of a digital camera and computer installed with software called Image Analyzer. Average Surface Roughness (R_a) of a machined workpiece is found using Tallysurf surface roughness tester. The parameters considered for the experimentation are speed, feed, depth of cut and type of insert. Speed, feed, and depth of cut are considered of 3 levels and type of insert is of 2 levels which are illustrated in table 2.

Table 2: Cutting Parameters with Levels

Parameters	Levels		
	1	2	3
Cutting speed(m/min)	70	110	150
Feed (mm/rev)	0.05	0.1	0.15
Depth of cut (mm)	0.1	0.2	0.3
Type of insert	1	2	

Cutting tool's flank wear and Surface roughness are considered as the responses of interest. An L18 orthogonal array is obtained taking partial factorial generated from the Design of Experiments using MiniTab 15. For the convenience in MiniTab, the TiN coated insert has been designated as 1 and the uncoated insert has been designated as 2. After experimentation of 18 iterations, the results obtained have been tabulated in table 3.

Table 3: L18 Orthogonal Array for Cutting Parameters and Response Variables

Type of Insert	Speed (m/min)	Feed (mm/rev)	DoC (mm)	Flank Wear (mm)	Surface Roughness (μm)
1	70	0.05	0.1	0.07	1.124
1	70	0.1	0.2	0.05	1.42
1	70	0.15	0.3	0.08	1.698
1	110	0.05	0.1	0.07	0.822
1	110	0.1	0.2	0.09	1.252
1	110	0.15	0.3	0.06	0.892
1	150	0.05	0.2	0.06	0.902
1	150	0.1	0.3	0.23	1.82
1	150	0.15	0.1	0.17	2.01
2	70	0.05	0.3	0.18	1.301
2	70	0.1	0.1	0.15	1.991
2	70	0.15	0.2	0.15	2.012
2	110	0.05	0.2	0.18	1.992
2	110	0.1	0.3	0.17	2.512
2	110	0.15	0.1	0.14	2.341
2	150	0.05	0.3	0.43	2.417
2	150	0.1	0.1	0.32	2.975
2	150	0.15	0.2	0.39	2.719

RESULTS AND DISCUSSIONS

Flank Wear Analysis

After the completion of the experimental iteration, the flank wear values have been observed for all the possible combinations involving the various turning parameters. The effect of these influencing parameters on the flank wear has been analyzed in ANOVA general linear model at a significance level of 95%. The regression equations were generated and the ANOVA table showing the predictable and functional values is obtained as shown in table 4.

Table 4: ANOVA Table for Flank Wear

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Type of insert	1	0.084050	0.084050	23.49	0.001
Speed	2	0.091078	0.045539	12.73	0.002
Feed	2	0.000044	0.000022	0.01	0.994
DoC	2	0.005878	0.002939	0.82	0.467
Error	10	0.035778	0.003578		
Total	17	0.216828			

Since the analysis was carried out at $\alpha=0.05$, all the parameters having a P-Value less than α will be significant. Based on the values observed from the Analysis of Variance table for flank wear, it is quite evident that the type of insert is the most influencing parameter on the flank wear with an F-Value of 23.49 followed by speed ($F=12.73$). It is also observed that the feed and depth of cut have no significant influence on the flank wear. Considering the above parameters the following regression equation is generated.

$$\begin{aligned} \text{Flank Wear} = & 0.1661 - 0.0683 \text{CC} + 0.0683 \text{UC} - 0.0528 v_{70} - 0.0478 v_{110} + 0.1006 v_{150} - \\ & 0.0011 f_{0.05} + 0.0022 f_{0.10} - 0.0011 f_{0.15} - \\ & 0.0128 d_{0.1} - 0.0128 d_{0.2} + 0.0256 d_{0.3} \end{aligned}$$

where,

CC-Type of insert 1 UC-Type of insert 2

v - cutting speed in m/min f - feed in mm/rev

d - depth of cut in mm.

From the surface and interaction plots shown in the Figure 2, it is found that the coated carbide insert has a better performance in terms of flank wear as compared to uncoated insert at any given machining conditions. The increasing speed affects the flank wear proportionately such that at higher speeds the flank wear is more. This may be due to the rubbing effect between the chip-tool interface which produces high temperatures at high speeds. This high temperature causes excessive wear in the uncoated tool as the resistance to the rupture is lower, whereas in the case of the insert coated with TiN, the wear and thermal resistance are high. The flank wear is thus reduced at the cutting edge. This is also supported by Shivdev Singh. et al [3]. The trend of increase in flank wear with increasing speed is observed for both types of inserts. The variation in the increase of flank wear, is substantially large, in case of the uncoated insert when compared to the coated one. In the case of feed and a depth of cut, no definite trend is observed indicating that these parameters have negligible or no influence on the flank wear. This is clearly evident from the staggered interaction plot.

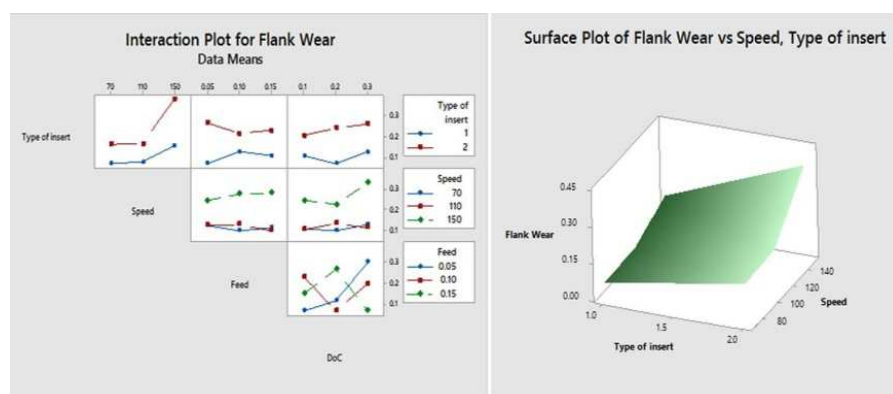


Figure 2: Interaction and Surface Plots for Flank Wear

The main effects plot for the flank wear in Figure 3 indicates the optimum combination of the machining parameters in response to the flank wears considering smaller the best as the acceptable condition.

The optimized parameters are TiN Coated insert with a cutting speed of 70 m/min, a feed of 0.15 mm/rev and a depth of cut of 0.2mm. The obtained optimized conditions are not a part of the L18 Orthogonal array considered for experimentation. Thus an additional run was done to find the optimum flank wear which is observed as 0.09mm for coated insert and 1.08mm for the uncoated insert.

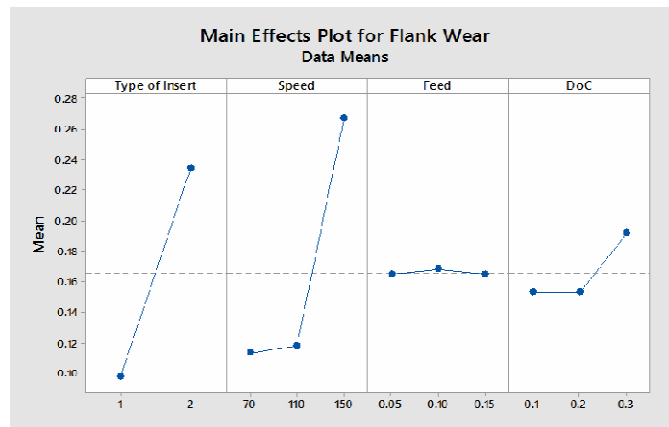


Figure 3: Main Effects Plot for Flank Wear

The Figure 4 shows the SEM image of the flank wear on Coated and uncoated carbide inserts at the optimized cutting parameters obtained from the main effects plot. It can be seen that the TiN coating has been retained and even the flank wear is observed to be very low. This may be due to a higher heat dissipation because TiN possesses a high thermal stability and conductivity with a low coefficient of friction which is lacking in the uncoated carbide insert. Due to the above factors, the adhesion between the tool and workpiece is reduced which further reduces the Built-up edge (BUE) formation in the coated insert. This agrees with Shivdev Singh. et al [3]. The low coefficient of friction at the chip-tool interface reduces the abrasion, thereby giving a higher performance of the coated insert at higher speeds in comparison with its counterpart [4].

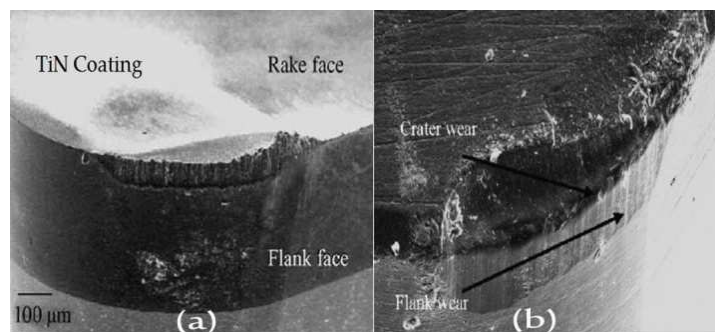


Figure 4: SEM Image of Tool Wear at Optimized Parameters:
(a) Coated Insert; (b) Uncoated Inserts

Surface Roughness Analysis

The effect of the influencing parameters on the surface roughness has been analyzed in ANOVA general linear model at a significance level of 95%. The regression equations were generated and the ANOVA table showing the predictable and functional values is obtained as shown in table 5. Based on the analysis of the surface roughness, the influencing parameters having the P-Value less than 0.05 are considered to be significant. Interestingly, three factors are found to be significantly affecting the surface roughness of which, the type of insert has been a predominant factor with a

functional value of 35.61. Feed is the next influencing factor after the type of insert with F-Value of 5.51 followed by the speed (F-Value 5.18). The depth of cut plays no significant role in the influence of surface roughness.

Table 5: ANOVA Table for Surface Roughness

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Type of insert	1	3.84569	3.84569	35.61	0.000
Speed	2	1.11853	0.55926	5.18	0.029
Feed	2	1.19042	0.59521	5.51	0.024
DoC	2	0.07994	0.03997	0.37	0.700
Error	10	1.07993	0.10799		
Total	17	7.31450			

Surface roughness (μm) = $1.7889 - 0.4622 \text{CC} + 0.4622 \text{UC} - 0.198v_{70} -$

$0.154v_{110} + 0.352v_{150} - 0.363f_{0.05} +$

$0.206f_{0.10} + 0.156f_{0.15} + 0.088d_{0.1} - 0.073d_{0.2} -$

$0.016d_{0.3}$

where,

CC-Type of insert 1 UC-Type of insert 2

v - cutting speed in m/min f - feed in mm/rev

d - depth of cut in mm.

The interaction and surface plots have been plotted as shown in figure 5. It is observed that the type of insert decides the quality of surface finish. At the moderate speeds, the surface finish is higher as compared to low and high speeds. This is due to the reduction in the cutting forces at moderate speeds, as suggested by SR Das et al. [7]. The same trend is observed in both the inserts, but the coated insert gives a better surface finish at all machining conditions due to the reduced wear at the tooltip and enhanced heat dissipations, in agreement to Abrar A Arshi et al. [5]. With the increasing feed, the surface roughness increases due to the plowing effect formed on the workpiece surface. Again the coated insert performs better than the uncoated insert.

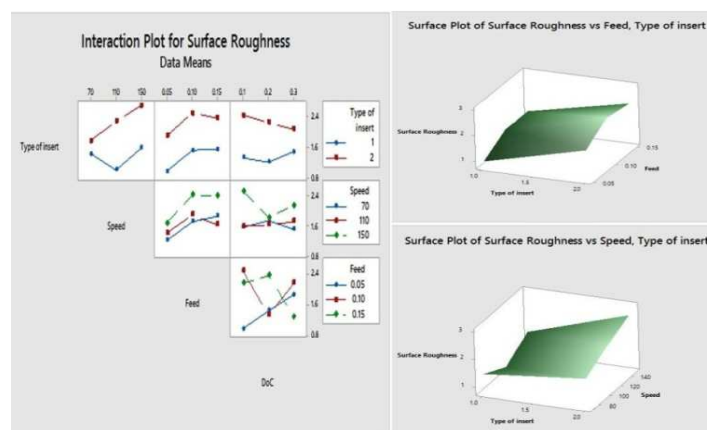


Figure 5: Interaction and Surface Plots for Surface Roughness

With smaller the better as the acceptable condition for surface roughness, the main effects plot has been plotted as shown in figure 6. which gives the following optimized parameters. Type of insert is coated, optimum speed is 70 m/min at a feed of 0.05mm/rev and a depth of cut of 0.2mm. Since this optimum combination is not a part of the initial L18 orthogonal array, an extra iteration was run to find out an optimum surface roughness. The value obtained using a coated insert is $0.75\mu\text{m}$ which is very close to that of a grinding operation. In case of the uncoated insert, the surface roughness is $1.125\mu\text{m}$.

SEM analysis is carried out for the workpiece machined by both coated and uncoated carbide inserts at the obtained optimized parameters. The image of which can be seen in figure 7. It is clearly evident that the surface finish is much better in coated machining. This is because, at the tool chip interface, the TiN coating suppresses excess heat a generation which leads to the reduction in a dissolution of the carbon particles from the insert [8]. Tool geometry and the cutting parameters affect the surface finish and at higher temperatures, the workpiece vibration and BUE formation make it difficult for machining the workpiece [9]. This is avoided in the coated insert because of high thermal stability, wear resistance and low coefficient of friction reduces the formation of BUE. Also, the coating provides self-damping capacity, which reduces the vibration. In figure 7 (b), long grooves and ridges can be seen, as a result of damaged cutting edge and excessive shearing in the shear plane resulting in the breaking of the carbon particles, eventually leading to plowing effect.

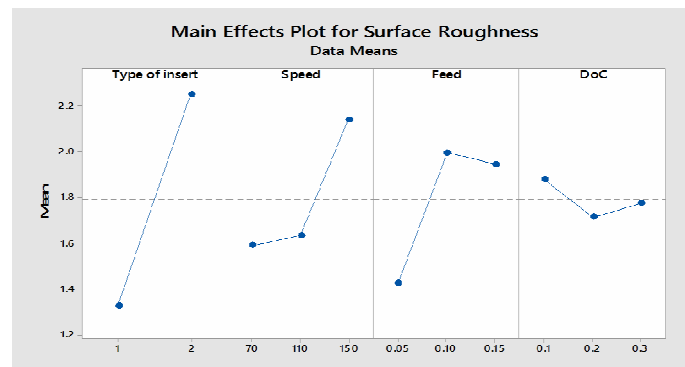


Figure 6: Main Effects Plot for Surface Roughness

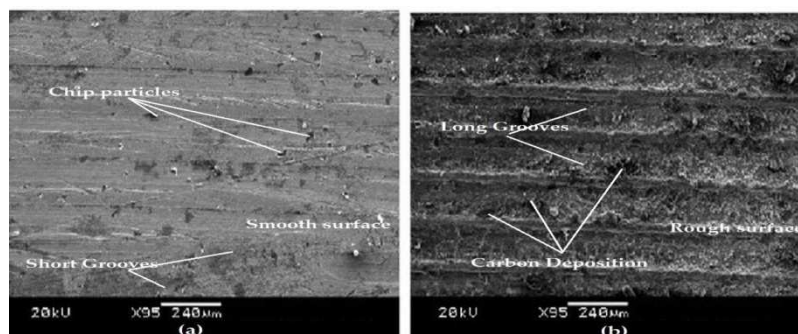


Figure 7: SEM images for Surface Roughness of the Workpiece at the Optimized Parameters:
(a) Using Coated Insert; (b) Using Uncoated Insert

CONCLUSIONS

The turning operation is performed on AISI 4340 steel rods of length 250 mm and a diameter of 25 mm. The turning is carried out using a TiN coated and uncoated carbide inserts with the cutting parameters of speed, feed, and depth of cut of 3 levels using an L18 orthogonal array. The surface roughness (R_a) and Flank wear (VB) have been

considered as a response of interests. The following conclusions have been arrived at:

- From the obtained ANOVA table for Flank wear, the most influencing parameter is the type of insert followed by speed having F-Values 23.49 and 12.73 respectively. This shows flank wear varies with the type of insert and speed, in a way that increasing speed increases the flank wear. The difference of the increasing trend in the flank wear is much higher in the uncoated tool.
- For surface roughness, type of tool has the highest significance among the parameters with 100% significance (P-Value 0.000) followed by feed (F-Value of 5.51) and speed (F-Value 5.18). At moderate speeds, the surface roughness is lower compared to low and high speeds. Increasing feeds to increase the surface roughness but it is always lower in the case of coated inserts.
- The optimized parameters for flank wear obtained are TiN Coated insert with a cutting speed of 70 m/min, a feed of 0.15 mm/rev and depth of cut of 0.2mm which are not a part of the orthogonal array. The flank wear values in case of both the inserts are 0.09mm for coated insert and 1.08mm for the uncoated insert.
- Coated inserts at a speed 70 m/min, a feed of 0.05mm/rev and a depth of cut of 0.2mm are the optimum parameters obtained for surface roughness. The surface roughness values for the coated insert is 0.75 μm and for the uncoated insert is 1.125 μm .
- The SEM analysis of the tool shows excessive flank wear for the uncoated insert as compared to the coated insert. This is due to excellent wear resistance and low coefficient of friction of TiN in extreme machining conditions.
- The SEM analysis of workpiece clearly indicates a smoother surface when machined with a coated carbide insert. This is because the high thermal stability of TiN coating reduces the BUE formation and provides self-damping capacity to reduce the vibrations at higher speeds.
- For any given conditions, the performance of coated carbide insert is always better than the uncoated insert. This in turn, may enhance the tool life, productivity and the quality of machining when used in hard turning.

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